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# Numerical and experimental investigations of thermally induced oscillating flow inside a capillary tube

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## ABSTRACT

A numerical model has been developed for a system consisting of a liquid slug and a vapour plug oscillating in a tube closed at one end, and connected to a reservoir at a constant pressure at the other end, which represents the most basic configuration of a Pulsating Heat Pipe (PHP). The thermally driven self-sustained oscillations of the system result from evaporation and condensation phenomena occurring at two zones of the tube (separated by an adiabatic section), one being cooled and the other being heated, simultaneously. The modelling principles of this system had been posed in previous works. In this work, the equation describing the liquid film evaporation has been substantially improved in the light of recent experimental results: both, the thickening of the film and the shortening of its length due to the evaporation at the triple line are taken into account. Furthermore, the transient heat conduction equation is solved in both the tube and the liquid film in order to calculate the temperature of the evaporator, which is a key parameter of the model. Moreover, an experimental bench is presented to measure the pressure variations inside an oscillating liquid slug. The results show that the classical correlations of fluid mechanics are relevant to model the oscillation of this system. Finally, a parametric study is carried out to understand the influence of the thermal properties of both the liquid and the tube on the start-up of the system. The thermal effusivity of both these materials is found to be an important criterion to indicate the conditions under which oscillations can commence and relain self-sustained.

## 1. Introduction

A pulsating heat pipe (PHP) is a non-equilibrium passive two-phase heat transfer device, belonging to a category of wickless heat pipes, however with complex internal thermo-hydraulic transport processes. Thermally driven self-sustained oscillating two-phase Taylor bubble flow is the nature of two-phase flow mostly encountered in these systems, which leads to its unique heat transfer characteristics. A detailed review on advanced and unsolved issues in pulsating heat pipes was written by Zhang and Faghri [1]. It was shown that the number of relevant parameters to characterize a PHP is so large that it is difficult to explicitly discriminate the effect of one parameter among the others. The geometrical parameters of the device (diameter, length, number of turns, etc.), the boundary conditions and the thermophysical properties of the fluid are of major importance [2]. As a result, most of the numerical models developed at the scale of the system fail to simulate the behaviour of PHPs in a large range of geometries and boundary conditions. The system modelling approach has failed so far to provide a universal understanding of the PHP because the basic physical phenomena and the extent of parameters responsible for system dynamics are not yet well understood.

The instability that causes the oscillations is yet to be scrupulously studied in the literature. Therefore, more detailed quantitative information on the local menisci and film dynamics inside the PHP is lacking. One has to begin with a system of a minimal complexity which is a straight capillary heated from one end and cooled from the other end containing one vapour bubble and one liquid slug. In the following, this system will be named “single-branch PHP”. Although such a system seems to be simple, it represents the essential operational element of the multi-bubble PHP system. One can mention evaporation/condensation of liquid continuous menisci and wetting films, motion of menisci and

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**Nomenclature**

| | |
|---|---|
| A | Cross section, ($m^2$) |
| $a_c$ | Accommodation coefficient, (-) |
| $c_p$ | Specific heat at constant pressure, (J/kg.K) |
| $c_v$ | Specific heat at constant volume, (J/kg.K) |
| C | Thermal capacitance per unit length, (J/m.K) |
| $C_f$ | Coefficient of friction, (-) |
| d | Diameter, (m) |
| F | Force, (N) |
| g | Acceleration due to gravity, ($m/s^2$) |
| h | Heat transfer coefficient, ($W/m^2.K$) |
| H | Height (m) |
| $h_{lv}$ | Enthalpy of vaporization or condensation, (J/kg) |
| j | Temporal node number, (-) |
| K | Thermal conductance, (W/K) |
| L | Length, (m) |
| $\overline{M}$ | Molecular weight, (kg/mol) |
| m | Mass, (kg) |
| $\dot{m}$ | Mass flow rate, (kg/s) |
| n | Number of nodes, (-) |
| P | Pressure, ($N/m^2$) |
| R | Thermal resistance, (K.m/W) |
| $\overline{R}$ | Universal gas constant, (8.314 J mol/K) |
| Re | Reynolds number, (-) |
| t | Time (s) |
| T | Temperature, (°C) |
| u | Velocity (m/s) |
| x | Location with $x = 0$ at the tube end, (m) |
| X | Location with $X = 0$ at adiabatic/condenser boundary, (m) |
| z | Spatial node number, (-) |

*Greek symbols*

| | |
|---|---|
| $\delta$ | Thickness, (m) |
| $\theta$ | Contact angle, (rad) |
| $\lambda$ | Thermal conductivity, (W/m.K) |
| $\mu$ | Dynamic viscosity, (Pa.s) |
| $\rho$ | Density, ($kg/m^3$) |
| $\sigma$ | Surface tension, (N/m) |
| $\tau$ | Shear stress, ($N/m^2$) |
| $\Phi$ | Heat flux, (W) |

*Subscripts*

| | |
|---|---|
| a | Adiabatic section |
| c | Condenser/condensation |
| cond | Conduction |
| conv | Convection |
| d | Dead space due to connections |
| e | Evaporator/evaporation |
| ext | External |
| hs | Heat source |
| int | Internal |
| l | Liquid |
| lf | Liquid film |
| p | Pressure |
| r | Reservoir |
| reg | Regular |
| sat | Saturation |
| sens | Sensible |
| sing | Singular |
| t | Total |
| tb | Tube |
| tl | Triple line |
| v | Vapour |
| z | Spatial node number |

*Superscripts*

| | |
|---|---|
| 0 | Initial |
| J | Temporal node number |

contact lines, viscous friction during the slug motion among other phenomena that govern the PHP dynamics [3].

Some of these phenomena have been studied for non-moving menisci. Heat and mass transfer was extensively studied in the vicinity of stationary menisci in capillary structures of conventional heat pipes. In particular, the intense evaporation phenomena at the triple line formed by the meniscus in contact with the solid wall has been actively studied [4,5]. On the other hand, the motion of constrained bubbles in capillaries was well studied under isothermal conditions [6,7]. It has been discovered that the viscous dissipation inside the wetting films left on the tube walls behind the moving liquid meniscus makes an important contribution to the overall pressure drop. Furthermore, the dissipation (and the pressure drop) is larger when the meniscus advances along the dry wall with respect to the wall with already deposed wetting film. This shows the importance of the contact lines, the number of which might be large in a multi-bubbles PHP. The dewetting in capillaries, depending on both the nature of the fluid and the tube, is also considered [8]. The evaporation in the constrained bubble geometry is studied in the domain of convective boiling [9]. The oscillation of bubbles in isothermal conditions was studied by Lips and Bonjour [10]. However, the conjunction of phase-change and oscillating dynamic introduces new challenges.

From a modelling perspective, this coupled analysis was initiated by Zhang et al. [11,12] and Dobson [13,14], who studied theoretically the governing mechanisms of a single-branch PHP, consisting of one vapour bubble and one liquid slug. Das et al. [15] developed a similar approach including the two-phase equilibrium that occurs locally at the liquid-vapour interface, especially along the time-varying wetting thin film which gets laid down by the liquid slug during its journey from the evaporator towards the condenser and through which the major part of the heat and mass transfer occurs. This liquid film was shown to be responsible for the large flow oscillations observed in the system. In this work, an instability analysis of this system was also performed. The local scale modelling was further extended to several PHP branches with many liquid slugs and vapour bubbles [16–23].

Since 2010, the number of experimental works dealing with the physical phenomena occurring in a single-branch PHP increased remarkably [15,24–30]. This shows an acknowledgement by the scientific community of the necessity of fundamental studies related to the PHP. In 2010, Das et al. [15] were able to obtain thermally driven self-sustained oscillations in horizontal location in such a system under a definite range of operating experimental conditions. This experimental bench was further improved by Rao et al. [31,32] and Recklin et al. [33].

In the present paper, the model developed to theoretically study the governing mechanisms of a single-branch PHP [11–15] is further enhanced in the light of the recent experimental results and theoretical analyses presented by Rao et al. [31,32]: